Shell-model calculations with realistic low-momentum two-body effective interactions

- Shell-model calculations with realistic effective interactions: outline of theoretical framework

- Exotic nuclei beyond ^{132}Sn: comparison between theory (CD-Bonn potential + V_{low-k}) and experiment and predictions for future experiments

- Summary and outlook

Realistic shell-model calculations with two-body forces

↓

V_{eff} derived from the free nucleon-nucleon potential

↓

Two main ingredients

- Nucleon-nucleon potential
- Many-body theory: derivation of the effective interaction

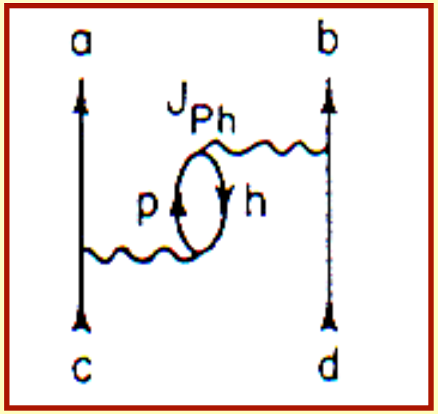
↓

No adjustable parameter in the calculation of two-body matrix elements

V_{eff} calculated by a well-established perturbative approach, the $\hat{Q}$-box folded-diagram expansion

In practical applications: diagrams first-, second-, and third-order in the interaction

V_{eff} should account for effects of the configurations excluded from the model space: core polarization effects



+ …

"Bubble"

Renormalization of the *NN* interaction
("Hard-core" potentials, e.g., CD-Bonn)

V_{low-k} **approach:** construction of a low-momentum *NN* potential V_{low-k} confined within a momentum-space cutoff $k \le \Lambda$.

V_{low-k} **preserves the physics of the original *NN* interaction up to a certain cut-off momentum** Λ**: the deuteron binding energy and low-energy scattering phase-shifts of** V_{NN} **are reproduced.**

V_{low-k} is a smooth *NN* potential

↓

Low-momentum effective interactions

Advantages of the V_{low-k} approach

1. V_{low-k} can be used directly in nuclear structure calculations within a perturbative approach.

2. The differences between matrix elements of different *NN* potentials practically disappear for the V_{low-k} matrix elements suggesting the realization of a nearly unique low-momentum *NN* potential.

↓

3. The V_{low-k}'s extracted from various phase-shift equivalent *NN* potentials give very similar results in nuclear structure calculations.

"Modern" *NN* potentials

Nijmegen I - (P_D = 5.66%); χ^2 / N_{data} = 1.03

Nijmegen II - (P_D = 5.64%); χ^2/N_{data} = 1.03

Argonne V_{18} - (P_D = 5.76%); χ^2/N_{data} = 1.09

CD Bonn - (P_D = 4.85%); χ^2/N_{data} = 1.02

NN potentials derived from chiral effective field theory

N^3LO potential (Entem & Machleidt, 2002-2003)

N^3LOW potential (Entem & Machleidt, 2005-2006)

N^3LO potential (E. Epelbaum, W. Glöckle, and U.-G. Meissner, 2005)

$NNLO_{opt}$ potential (May 2013)
$\chi^2 / N_{data} \approx 1$ $E_{lab} < 125$ MeV

PRL 110, 192502 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Optimized Chiral Nucleon-Nucleon Interaction at Next-to-Next-to-Leading Order

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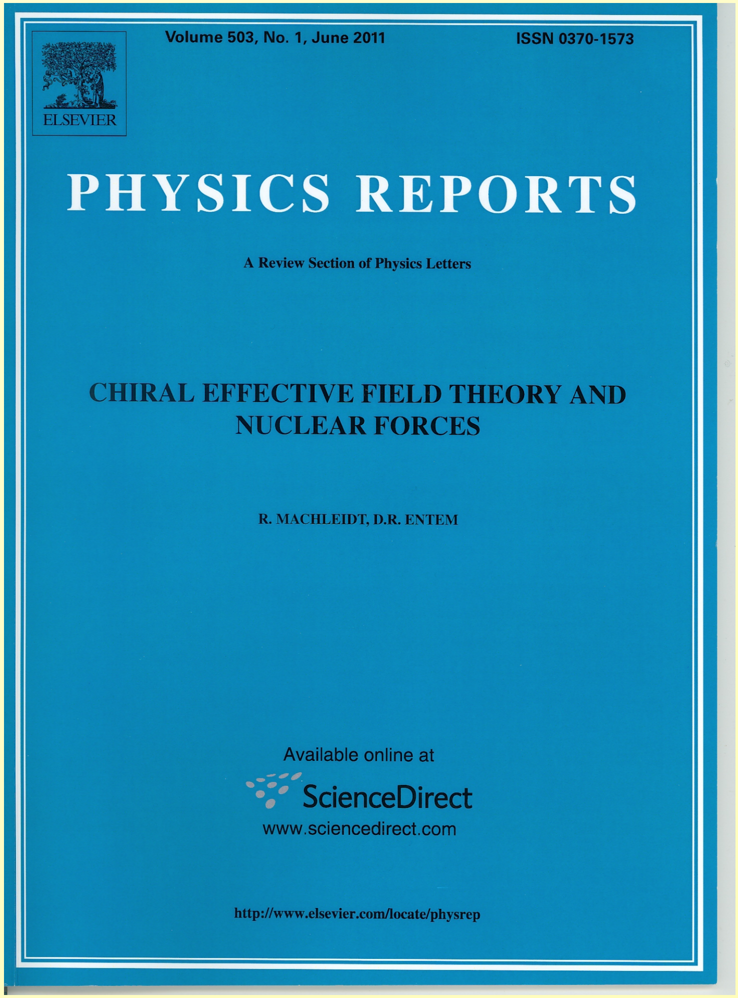
(Received 19 March 2013; published 7 May 2013)

We optimize the nucleon-nucleon interaction from chiral effective field theory at next-to-next-to-leading order (NNLO). The resulting new chiral force NNLO_{opt} yields $\chi^2 \approx 1$ per degree of freedom for laboratory energies below approximately 125 MeV. In the $A = 3, 4$ nucleon systems, the contributions of three-nucleon forces are smaller than for previous parametrizations of chiral interactions. We use NNLO_{opt} to study properties of key nuclei and neutron matter, and we demonstrate that many aspects of nuclear structure can be understood in terms of this nucleon-nucleon interaction, without explicitly invoking three-nucleon forces.



Volume 503, No. 1, June 2011 ISSN 0370-1573

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PHYSICS REPORTS

A Review Section of Physics Letters

CHIRAL EFFECTIVE FIELD THEORY AND NUCLEAR FORCES

R. MACHLEIDT, D.R. ENTEM

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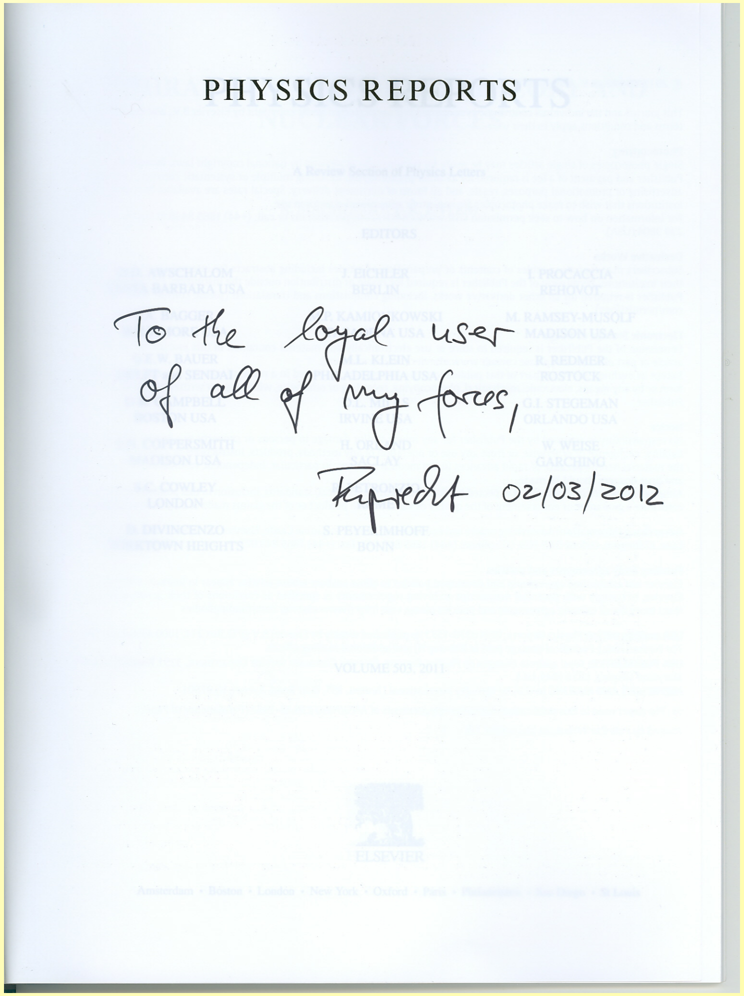

PHYSICS REPORTS

To the loyal user of all of my forces,

Ruprecht 02/03/2012

PHYSICAL REVIEW C **66**, 021303(R) (2002)

Microscopic nuclear structure based upon a chiral *NN* potential

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(Received 28 December 2001; published 12 August 2002)

We report on shell-model calculations employing effective interactions derived from a new realistic nucleon-nucleon (*NN*) potential based on chiral effective-field theory. We present results for ^{18}O, ^{134}Te, and ^{210}Po. Our results are in excellent agreement with experiment indicating a remarkable predictive power of the chiral *NN* potential for low-energy microscopic nuclear structure.

IdahoB

PHYSICAL REVIEW C **75**, 024311 (2007)

Low-momentum nucleon-nucleon interactions and shell-model calculations

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(Received 16 October 2006; published 27 February 2007)

In the last few years, the low-momentum nucleon-nucleon (*NN*) interaction $V_{\text{low-}k}$ derived from free-space *NN* potentials has been successfully used in shell-model calculations. $V_{\text{low-}k}$ is a smooth potential which preserves the deuteron binding energy as well as the half-on-shell *T* matrix of the original *NN* potential up to a momentum cutoff Λ. In this paper, we test a new low-momentum *NN* potential derived from chiral perturbation theory at next-to-next-to-next-to-leading order with a sharp low-momentum cutoff at 2.1 fm^{-1}. Shell-model calculations for the oxygen isotopes using effective Hamiltonians derived from both types of low-momentum potential are performed. We find that the two potentials show the same perturbative behavior and yield very similar results.

N^{3}LOW vs N^{3}LO+V$_{\text{low-k}}$

PHYSICAL REVIEW C **81**, 064303 (2010)

Shell-model calculations for neutron-rich carbon isotopes with a chiral nucleon-nucleon potential

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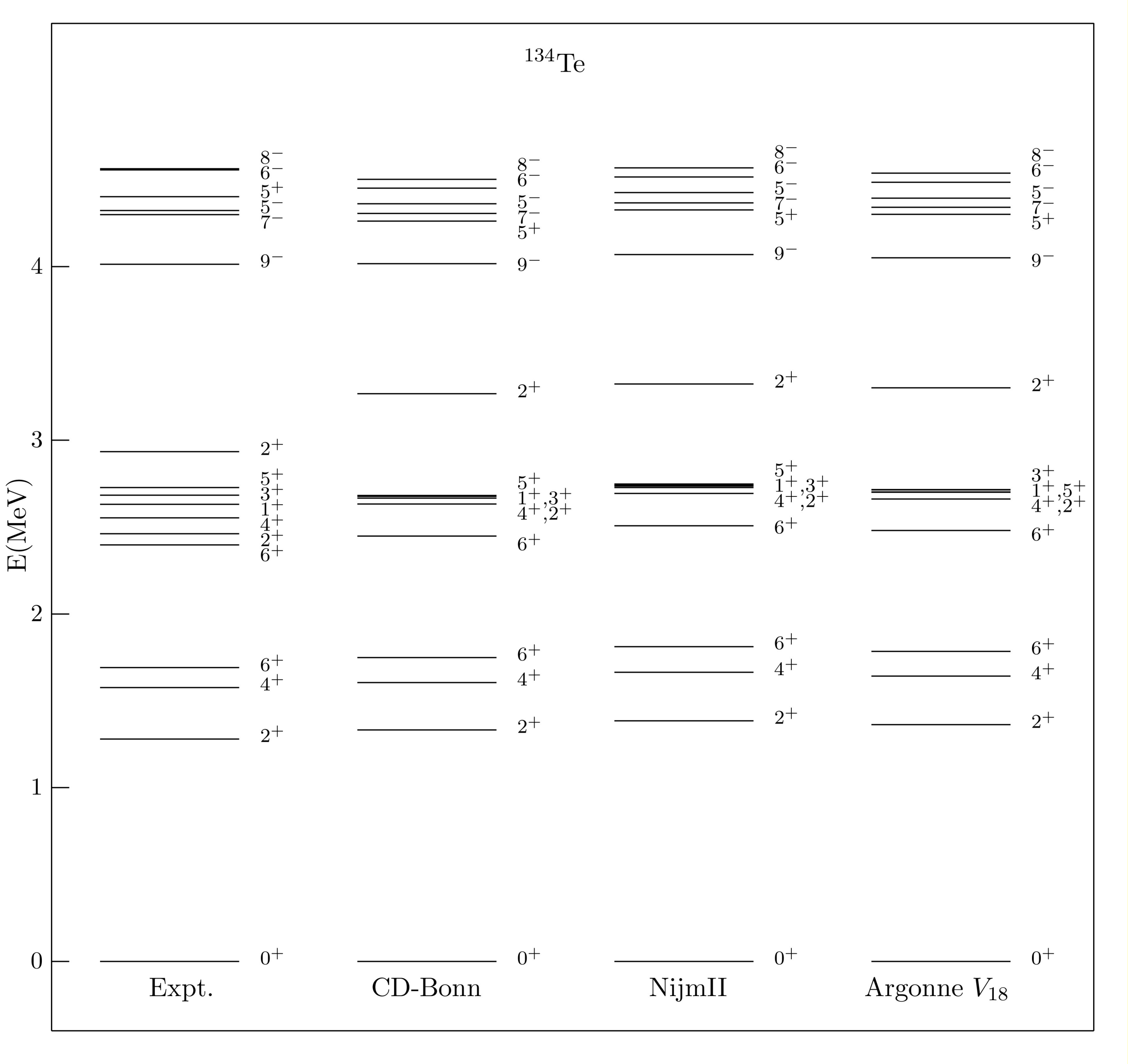
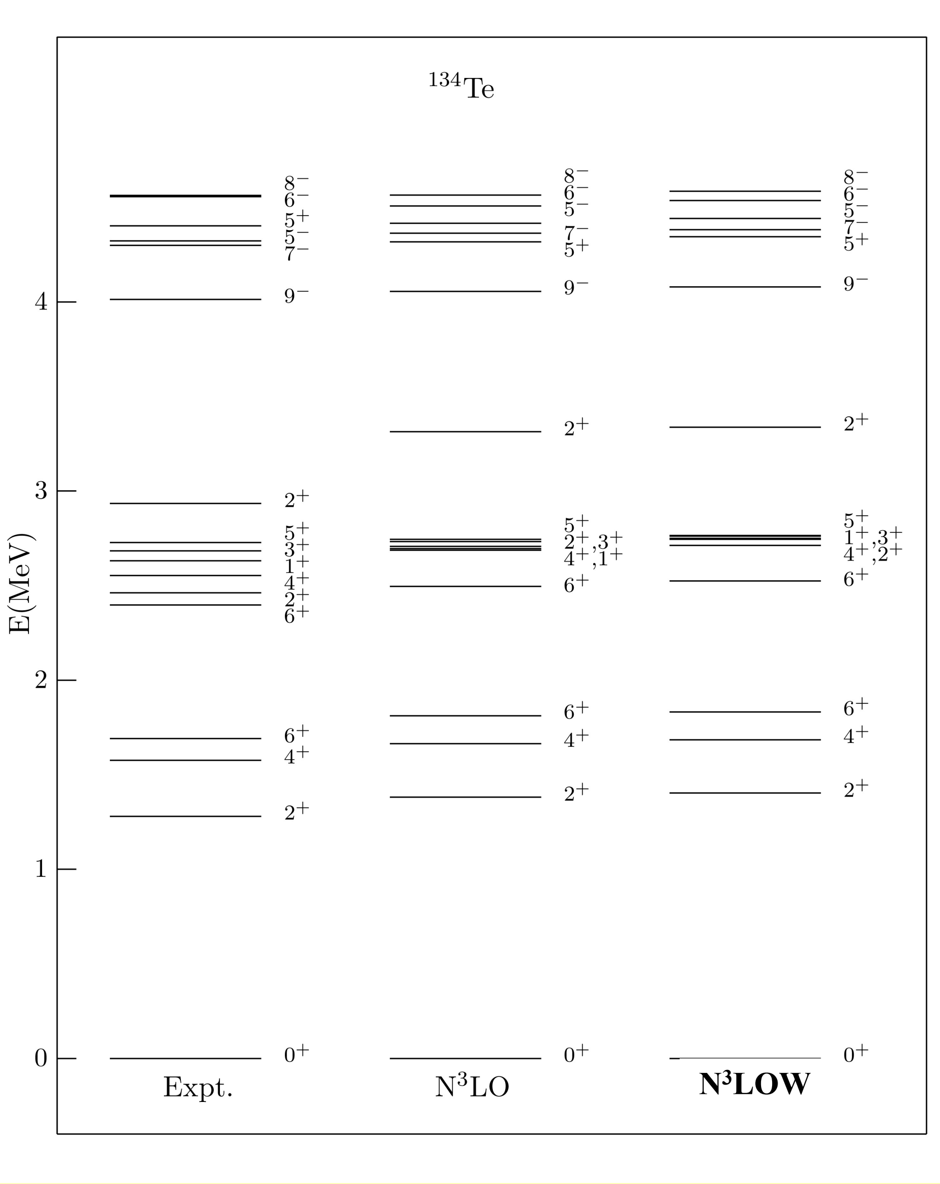
(Received 8 March 2010; revised manuscript received 31 March 2010; published 3 June 2010)

We have studied neutron-rich carbon isotopes in terms of the shell model employing a realistic effective Hamiltonian derived from the chiral N^{3}LOW nucleon-nucleon potential. The single-particle energies and effective two-body interaction have both been determined within the framework of the time-dependent degenerate linked-diagram perturbation theory. The calculated results are in very good agreement with the available experimental data, providing a sound description of this isotopic chain toward the neutron drip line. The correct location of the drip line is reproduced.

N^{3}LOW

V_{low-k} (Λ = 2.2 fm^{-1})





^{134}Te
E(MeV)
0
1
2
3
4
Expt.
N^{3}LO
N^{3}LOW
8$^-$
6$^-$
5$^+$
5$^-$
7$^-$
9$^-$
2$^+$
5$^+$
3$^+$
1$^+$
4$^+$
2$^+$
6$^+$
6$^+$
4$^+$
2$^+$
0$^+$
8$^-$
6$^-$
5$^-$
7$^-$
5$^+$
9$^-$
2$^+$
5$^+$
2$^+$,3$^+$
4$^+$,1$^+$
6$^+$
6$^+$
4$^+$
2$^+$
0$^+$
8$^-$
6$^-$
5$^-$
7$^-$
5$^+$
9$^-$
2$^+$
5$^+$
1$^+$,3$^+$
4$^+$,2$^+$
6$^+$
6$^+$
4$^+$
2$^+$
0$^+$

How far can we go in explaining nuclear structure properties with the simplest approach to realistic shell-model calculations?

i) Two-body potential + V_{low-k} (for hard-core potentials)

ii) Second-order in the $\hat{Q}-\mathrm{box}$ expansion

iii) Single-particle energies from experiment

Shell-model calculations with two-body effective interaction derived from the CD-Bonn potential through the V_{low-k} approach

^{132}Sn region

$\Lambda = 2.2$ fm^{-1}

Model space & single-particle energies

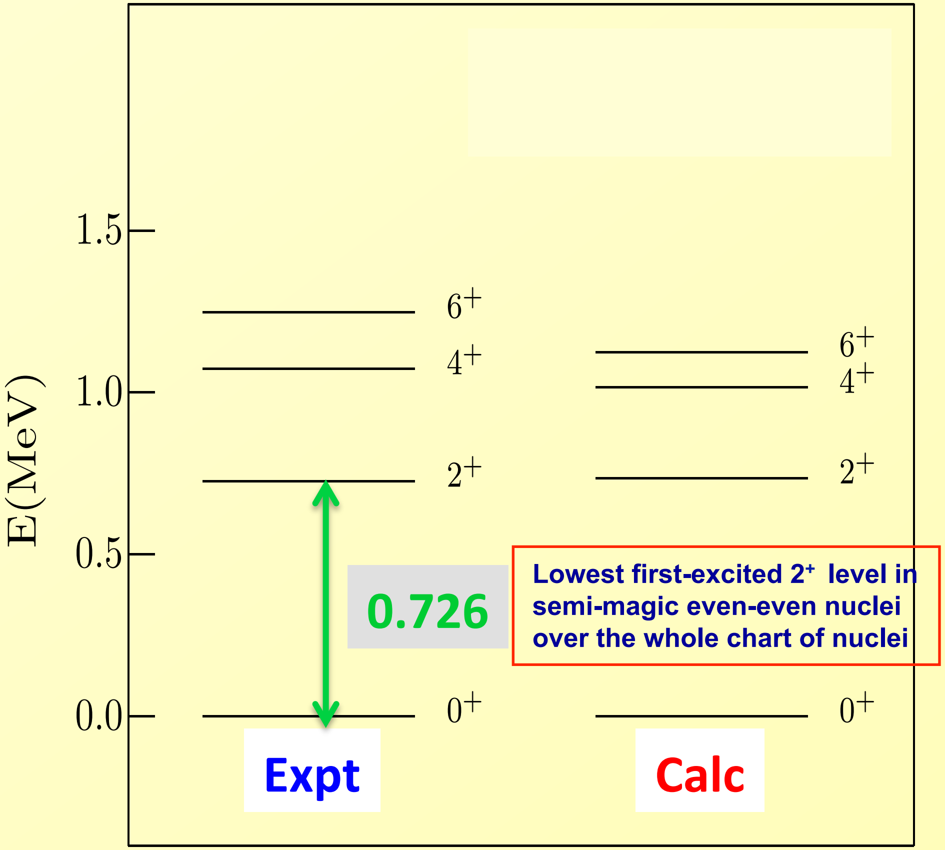
Valence neutrons in the $1f_{7/2}$, $2p_{3/2}$, $0h_{9/2}$, $2p_{1/2}$, $1f_{5/2}$, $0i_{13/2}$ levels of the 82-126 shell

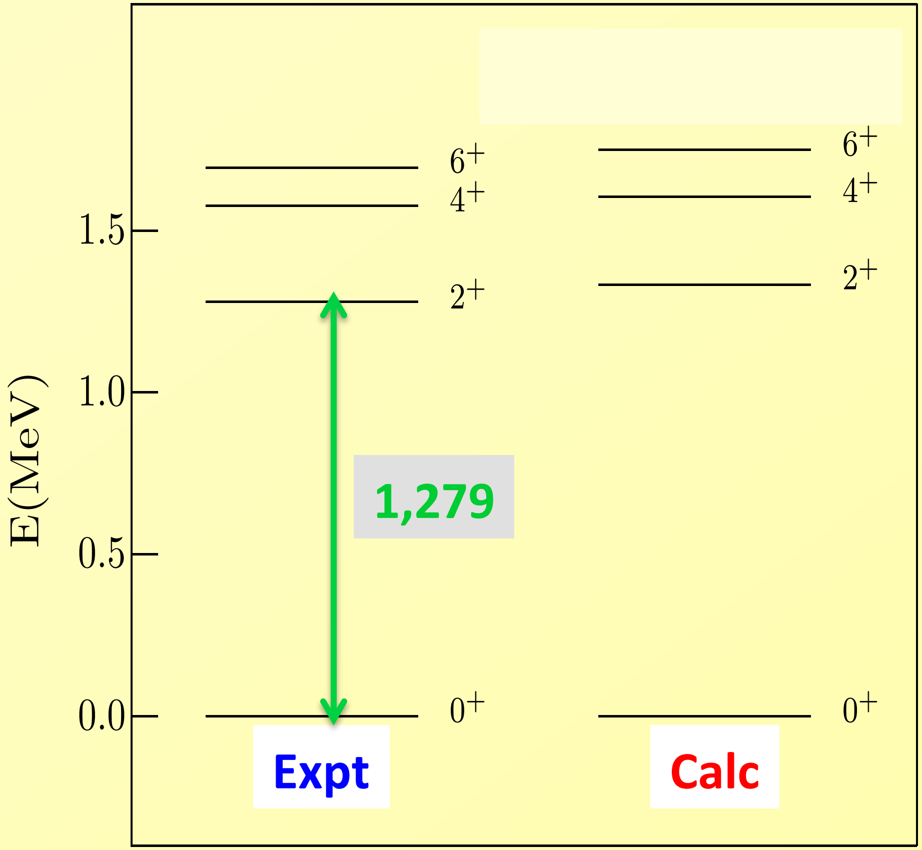
Protons in the $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $0h_{11/2}$, $2s_{1/2}$ of the 50-82 shell

Single-particle energies from the spectra of ^{133}Sb and ^{133}Sn

$^{134}_{50}Sn_{84}$

$^{134}_{52}Te_{82}$

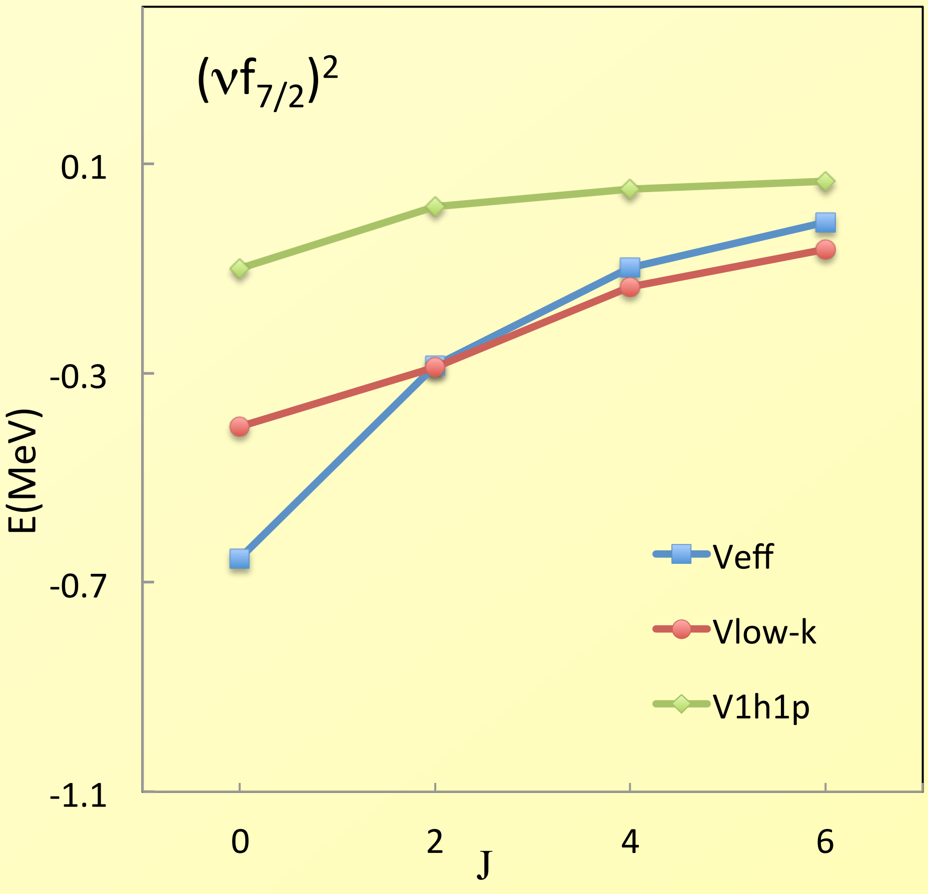


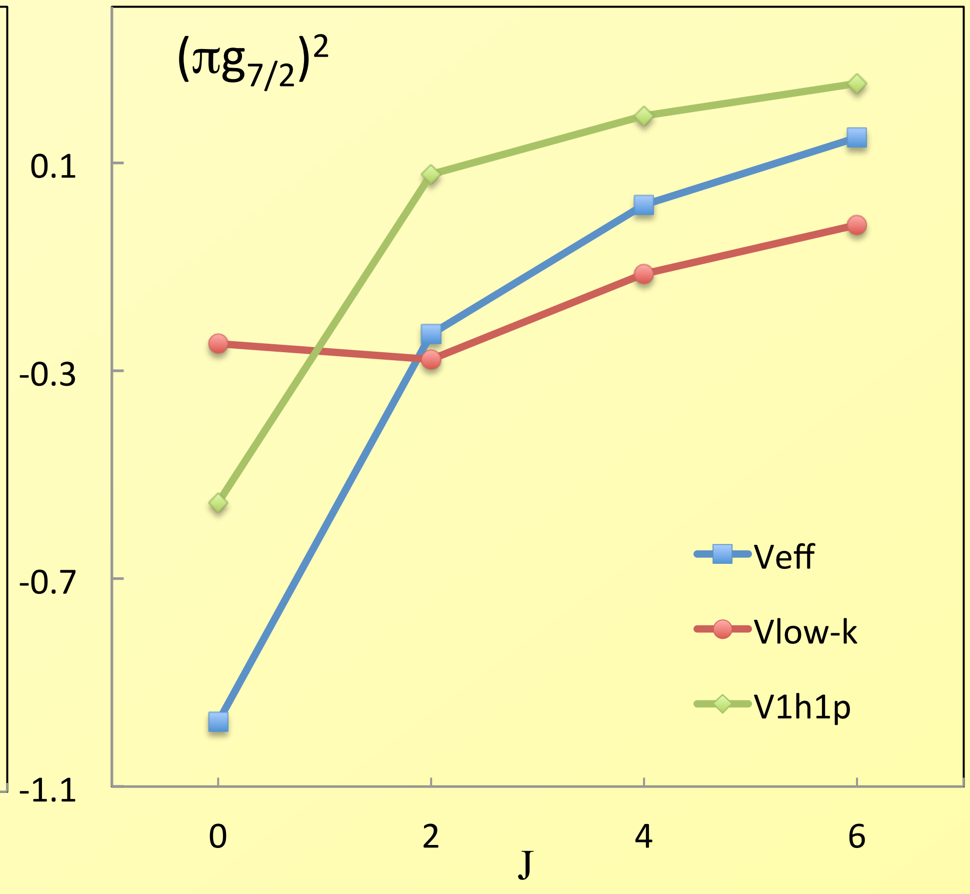


$(\nu f_{7/2})^2$ configuration

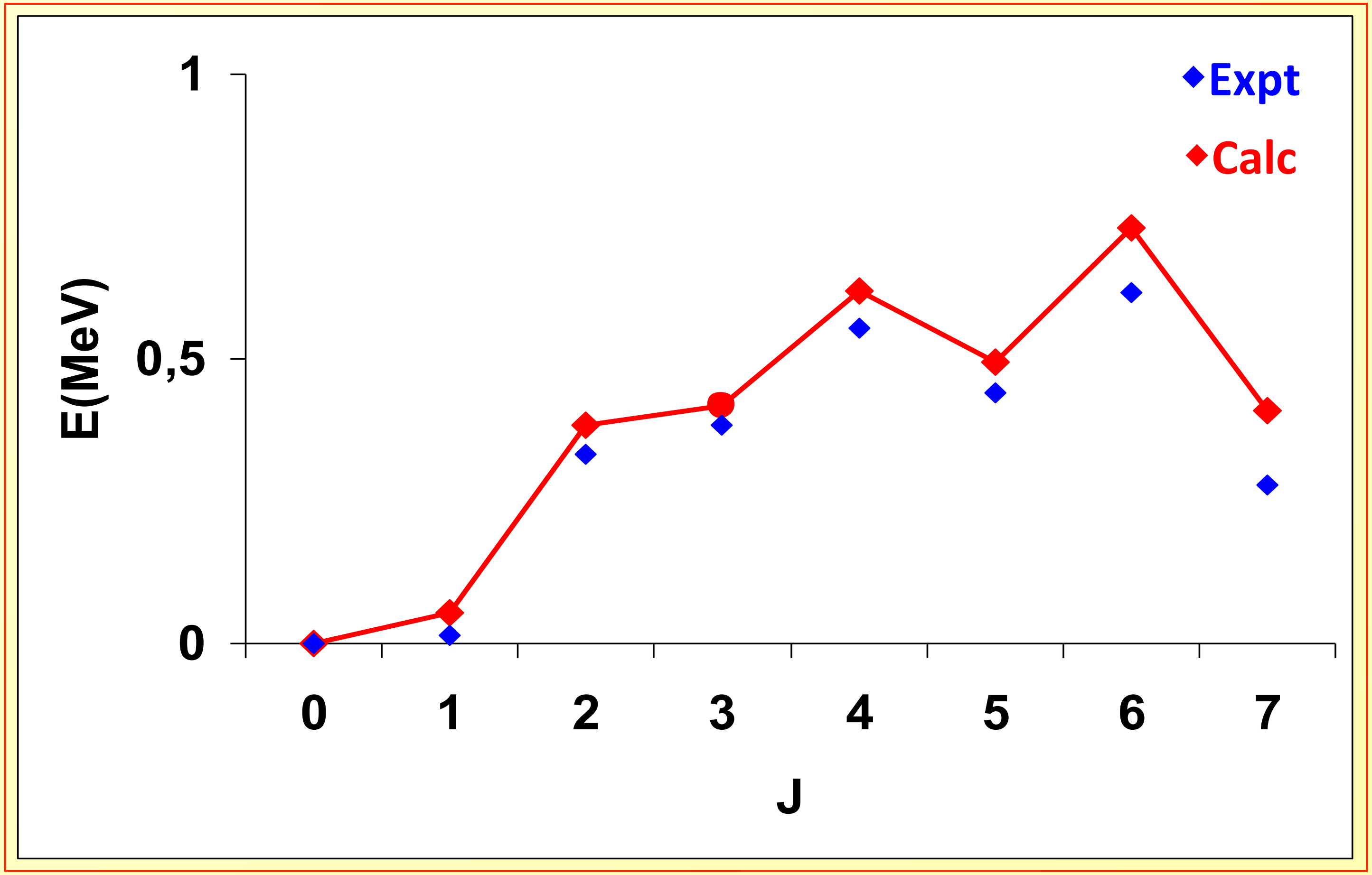
$(\pi g_{7/2})^2$ configuration

Diagonal matrix elements of interaction for the $(\nu f_{7/2})^2$ and $(\pi g_{7/2})^2$ configurations





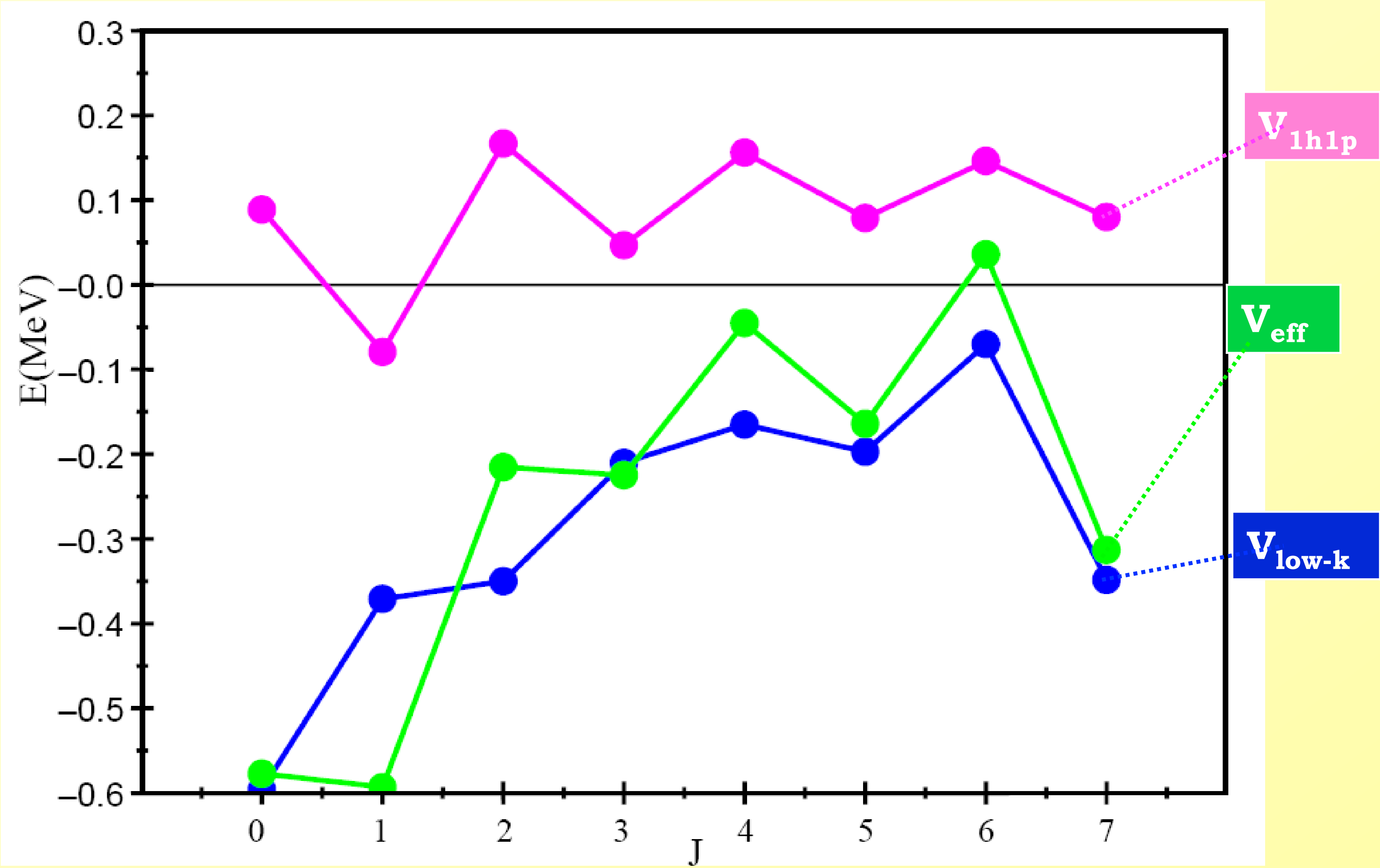
$^{134}_{51}Sb_{83}$

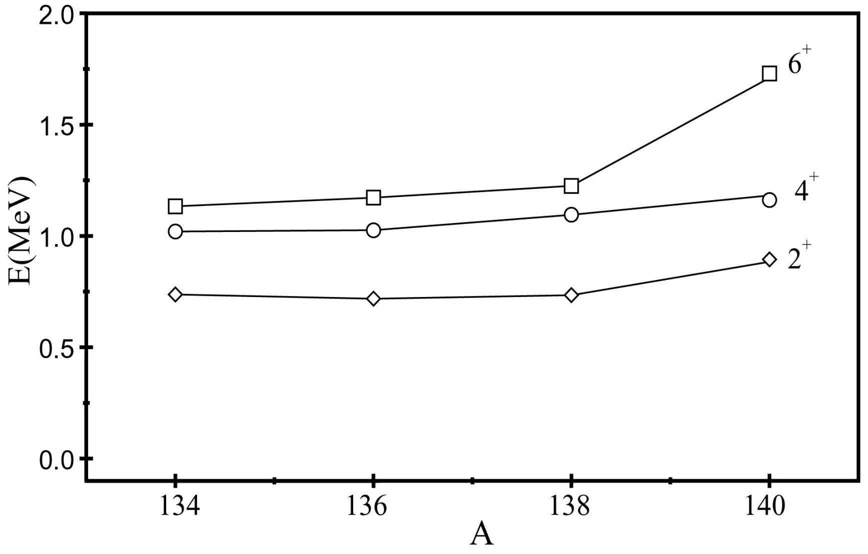


$\pi g7/2 \nu f7/2$ configuration

The 0^- ground state and the first excited 1^- state are nearly degenerate (13 keV energy difference)

Diagonal matrix elements of interaction for the $\pi g_{7/2} \nu f_{7/2}$ configuration





Calculated excitation energies of the yrast 2^+, 4^+, and 6^+ states in tin isotopes with $A = 134$, 136, 138 and 140.

No shell closure at N=90, in contrast with the results of other calculations

Binding energies and one-neutron separation energies (MeV) in Sn isotopes with A = 134, 136, 138, 140

	^{134}Sn	^{136}Sn	^{138}Sn	^{140}Sn
BE Calc	5.92	11.83	17.68	23.41
BE Expt	5.916 ± 0.150			
S_n Calc	3.55	3.55	3.53	3.50
S_n Expt	3.545 ± 0.152			

Some predictions for ^{134}Sn and ^{136}Sn

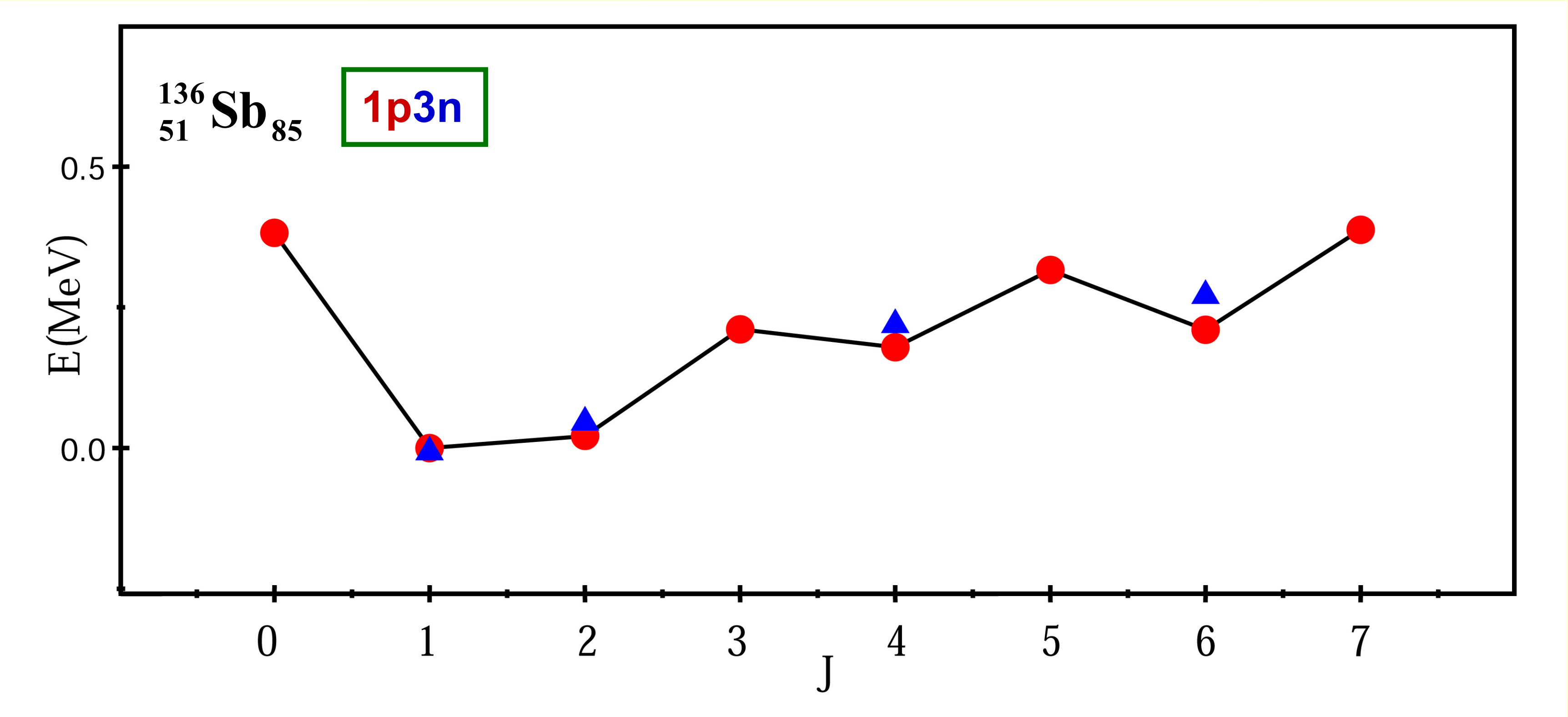
	^{134}Sn		^{136}Sn
	Expt	Calc	Calc
$B(E2:2_1^+ \rightarrow 0^+)$ [in W.u.]	1.4(2)	1.6	2.8
$B(E2:4^+ \rightarrow 2^+)$		1.7	0.83
$B(E2:6^+ \rightarrow 4^+)$	0.89(17)	0.82	0.12
$B(E2:2_2^+ \rightarrow 0^+)$		0.35	0.06
$B(E2:2_2^+ \rightarrow 2_1^+)$		2.93	1.8
$B(E2:2_2^+ \rightarrow 4^+)$		0.23	1.0
$B(M1:2_2^+ \rightarrow 2_1^+)$		0.02	0.09×10^{-2}
$Q(2_1^+)$ [in eb]		-0.02	-0.13
$Q(2_2^+)$		-0.03	+0.06
$\mu(2_1^+)$ [in nm]		-0.57	+0.46
$\mu(2_2^+)$		-0.25	+0.54

Tren

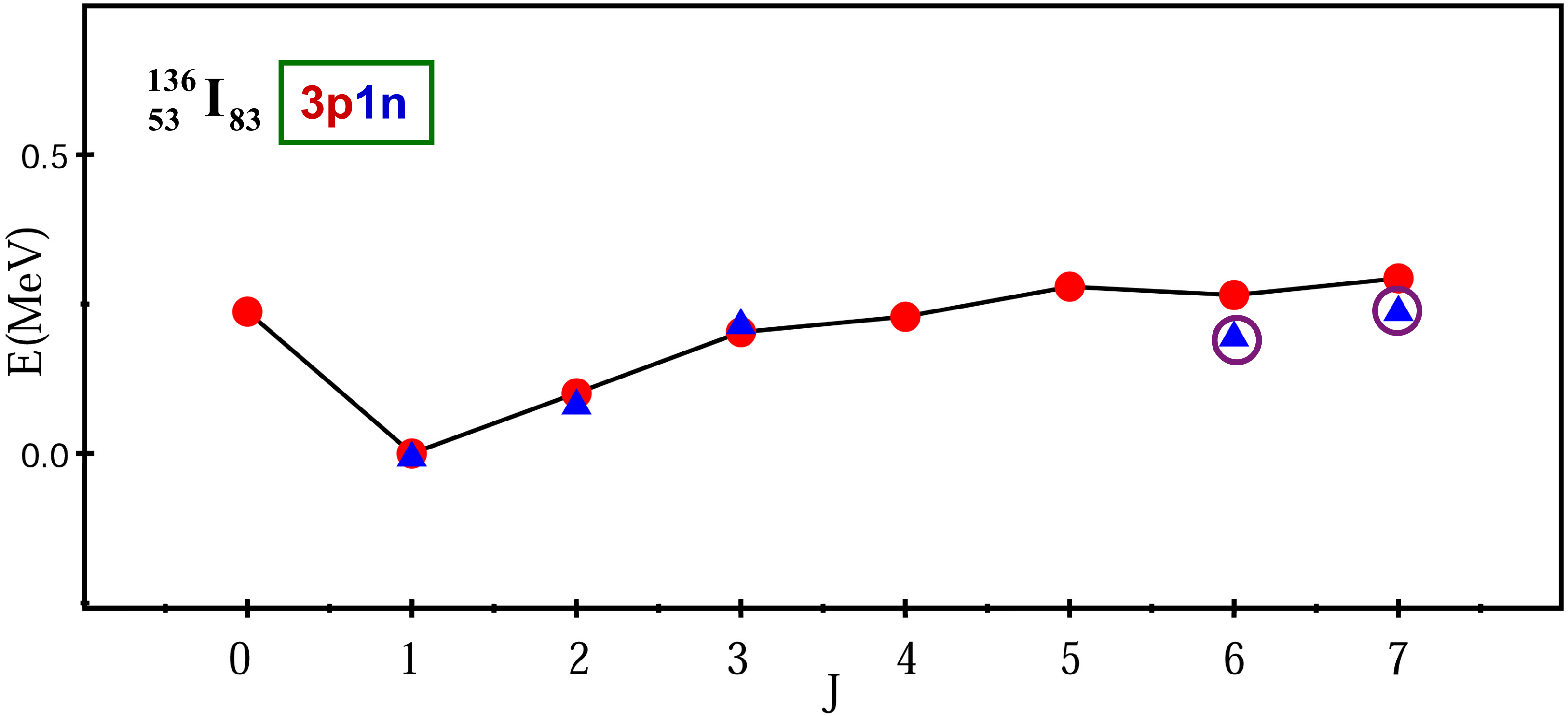
^{134}Te

B(E2 values (in W.u.)

$J_i \rightarrow J_f$	Calc.	Expt.
0+ → 2+	20	24±3
4+ → 2+	4.3	4.3±0.30
6+ → 4+	1.9	2.05±0.03



136Sb is at present the most exotic open-shell nucleus beyond 132Sn for which information exists on excited states



$^{136}_{53}I_{83}$
3p1n
0.5
0.0
E(MeV)
0
1
2
3
4
5
6
7
J

PHYSICAL REVIEW VOLUME 175, NUMBER 4 20 NOVEMBER 1968

^{137}Xe

4p1n

^{136}Xe(d,p) and ^{136}Xe(d,t) Reactions*

P. A. Moore† and P. J. Riley†
University of Texas, Austin, Texas 78712

AND

C. M. Jones and M. D. Mancusi‡
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

AND

J. L. Foster, Jr.
University of Pittsburgh, Pittsburgh, Pennsylvania 15213

(Received 8 July 1968)

States of ^{137}Xe and ^{135}Xe have been investigated via the ^{136}Xe(d,p) and ^{136}Xe(d,t) reactions with 13-MeV incident deuterons and an over-all energy resolution of 45 keV. Q values of 1.637±0.020 and −1.723±0.020 MeV have been obtained for the respective ground state ^{136}Xe(d,p)^{137}Xe and ^{136}Xe(d,t)^{135}Xe reactions. The angular distribution data have been analyzed using finite-range distorted-wave Born-approximation (DWBA) calculations corrected for nonlocality of the optical potential to extract spectroscopic information. Spin and parity assignments, excitation energies, and spectroscopic factors for most of the observed levels are presented. A ^{136}Xe(d,p) excitation function showed no significant evidence for an anomaly in the (d,p_0) cross section near the threshold of the (d,n) reaction to the corresponding isobaric analog state.

Trento13

Z. Phys. A – Hadrons and Nuclei 340, 339–340 (1991)

Zeitschrift für Physik A Hadrons and Nuclei
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Short note

Investigation of the (*d*, *p*)-reaction on $^{136,132}Xe$ in inverse kinematics*

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Received May 14, 1991; revised version July 2, 1991

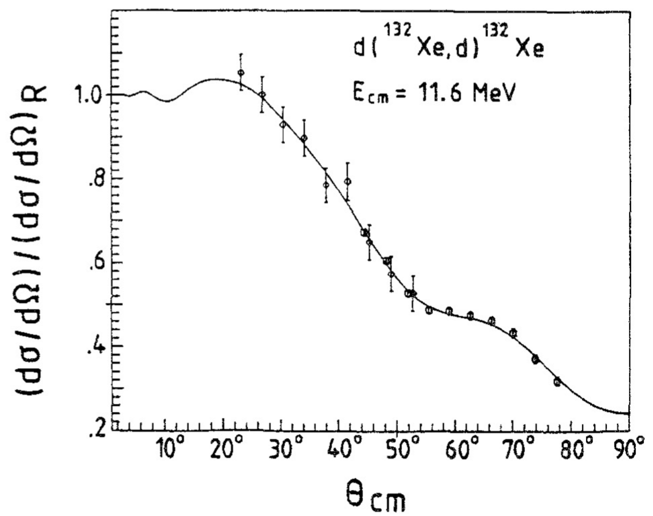
Abstract

The one-neutron transfer reactions $d(^{132,136}Xe, p)^{133,137}Xe$ have been investigated in inverse kinematics with xenon beams incident on deuterium loaded titanium targets. The angular distributions of the protons, measured with a detector array of 100 PIN-photodiodes, have been analyzed using standard DWBA. Generally, good agreement is obtained with results previously obtained in reactions induced by light-ion beams.

PACS: 25.45.Gh;25.70.Cd

The new GSI-accelerator SIS in combination with the fragment separator FRS and the experimental storage ring ESR will provide cooled beams of relatively short - lived nuclei, extending to isotopes far off stability. These beams open the possibility for nuclear structure studies on radioactive nuclei through direct reactions in inverse kinematics.
Of particular interest are investigations of single-nucleon transfer reactions near doubly-magic nuclei, as for instance the determination of single-particle energies and matrix elements of the two-body residual interaction in the vicinity of ^{132}Sn (N = 82, Z = 50), and of inelastic scattering studies of low-lying collective states.

contacts and for all columns at their P - contacts. The 10 lines delivered the time signals, the 10 columns the energy signals and by a coincidence - condition the identification of the diode which had fired was obtained. A more detailed description of the detector and the readout - method is given in ref. 1.



Trento13

PHYSICAL REVIEWC **84**, 024325 (2011)

Single-neutron energies outside ^{136}Xe

B. P. Kay,[1,*] J. P. Schiffer,[1] S. J. Freeman,[2] C. R. Hoffman,[1] B. B. Back,[1] S. I. Baker,[1] S. Bedoor,[3] T. Bloxham,[4] J. A. Clark,[1] C. M. Deibel,[1,5] A. M. Howard,[2] J. C. Lighthall,[1,3] S. T. Marley,[1,3] K. E. Rehm,[1] D. K. Sharp,[2] D. V. Shetty,[3] J. S. Thomas,[2] and A. H. Wuosmaa[3]

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(Received 4 July 2011; published 29 August 2011)

The single-neutron properties of the $N = 83$ nucleus ^{137}Xe have been studied using the ^{136}Xe(d,p) reaction in inverse kinematics at a beam energy of 10 MeV/u. The helical-orbit spectrometer, HELIOS, at Argonne National Laboratory was used to analyze the outgoing protons, achieving an excitation-energy resolution of ~100 keV. Extraction of absolute cross sections, angular distributions, and spectroscopic factors has led to a more complete understanding of the single-neutron strength in ^{137}Xe. In particular, the centroids of the $\nu h_{9/2}$ and $\nu i_{13/2}$ strengths appear to evolve through the $N = 83$ isotones in a manner consistent with the action of the tensor force.

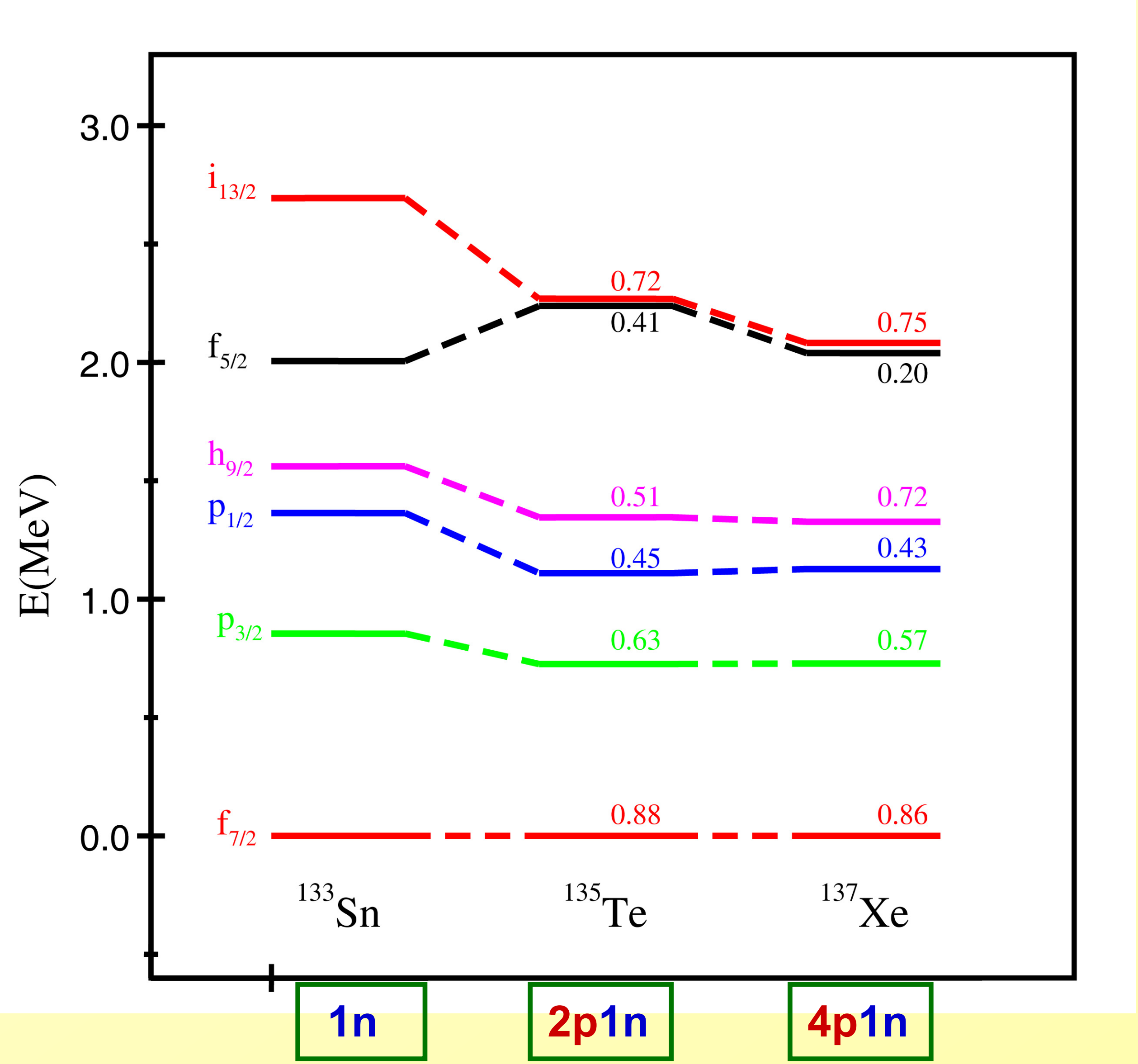
DOI: 10.1103/PhysRevC.84.024325 PACS number(s): 25.45.Hi, 21.60.Cs, 27.60.+j

Calculated energies and spectroscopic factors for ^{137}Xe compared with those obtained by Kay et al.

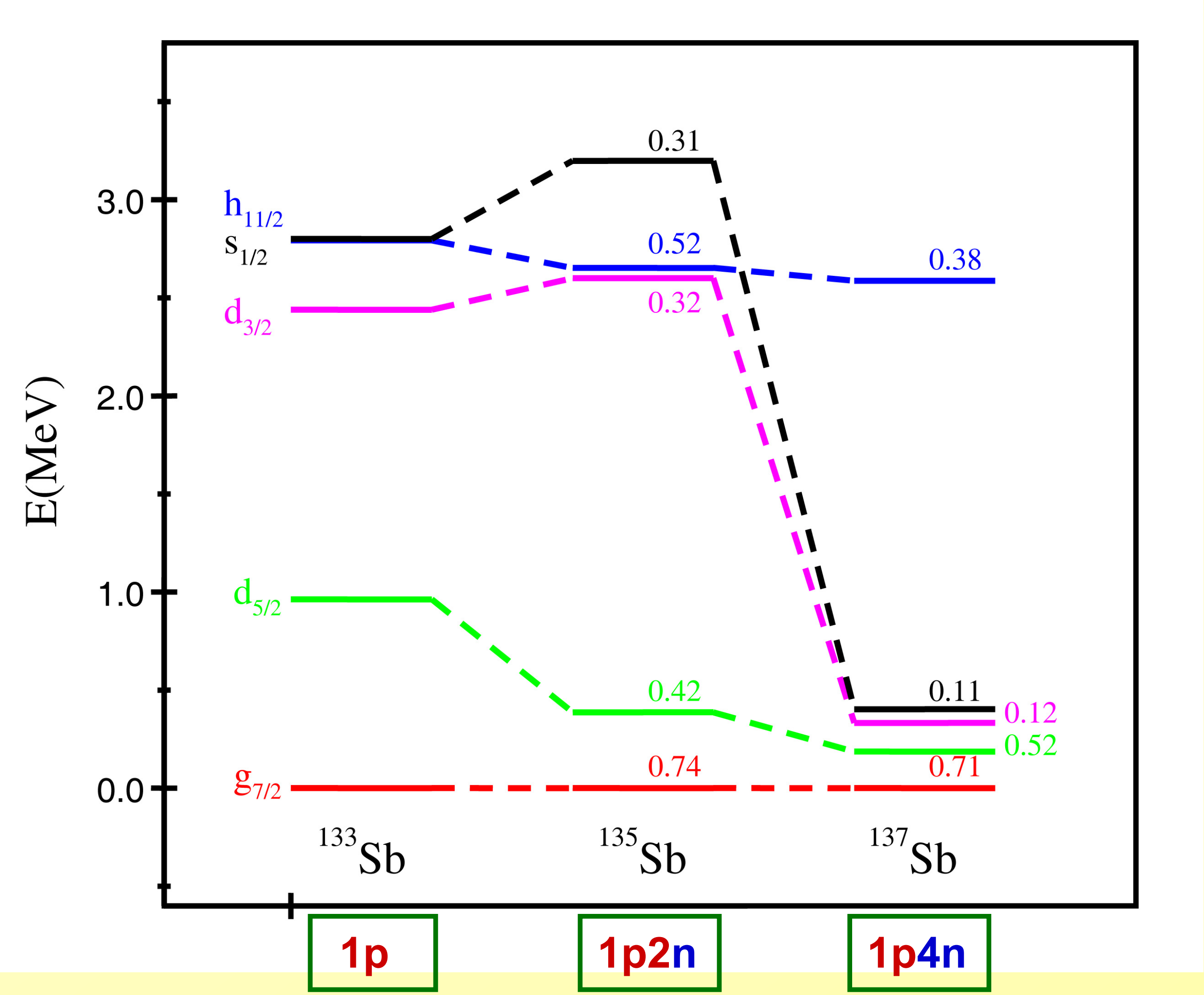
Expt.			Calc.		
J^{π}	E(MeV)	C^2S	J^{π}	E(MeV)	C^2S
$7/2^-$	0.000	0.94	$7/2^-$	0.000	0.86
$3/2^-$	0.601	0.52	$3/2^-$	0.728	0.57
$1/2^-,3/2^-$	0.986	0.35	$1/2^-$	1.127	0.43
$9/2^-$	1.218	0.43	$9/2^-$	1.327	0.72
$5/2^-$	1.303	0.22	$5/2^-$	1.349	0.17
$5/2^-,7/2^-$	1.534	0.12	$7/2^-$	1.589	0.05
			$5/2^-$	1.666	0.04
$(9/2^-)$	1.590	0.24	$9/2^-$	1.584	0.01
$(13/2^+)$	1.751	0.84	$13/2^+$	2.082	0.75

L. Coraggio, A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C 87, 034309 (2013)

Evolution of single-particle states beyond ^{132}Sn

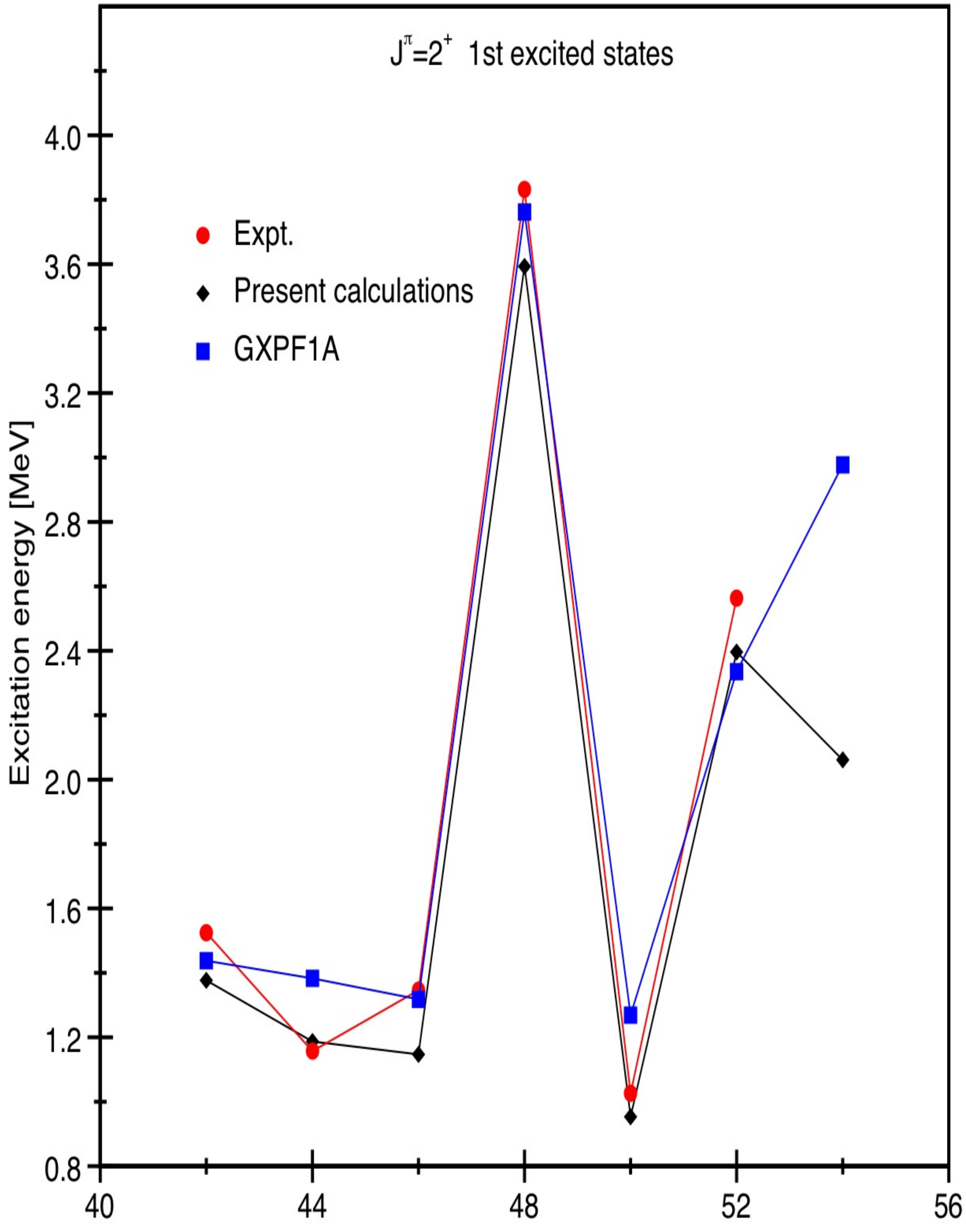


L. Coraggio, A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C 87, 034309 (2013)



E(MeV)
3.0
2.0
1.0
0.0
h11/2
s1/2
d3/2
d5/2
g7/2
0.31
0.52
0.38
0.32
0.42
0.11
0.12
0.52
0.74
0.71
133Sb
135Sb
137Sb
1p
1p2n
1p4n

Trento13



J$^{\pi}$=2$^+$ 1st excited states
Expt.
Present calculations
GXPF1A
Excitation energy [MeV]
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
40
44
48
52
56

Summary and Outlook

- The properties of exotic nuclei beyond ^{132}Sn are remarkably well described by a unique consistent shell-model Hamiltonian derived from a realistic free *NN* potential (CD-Bonn) renormalized through the V_{low-k} procedure. This gives confidence in its predictive power.

- At present no real evidence of shell modifications in the ^{132}Sn region. Our calculations, in line with the estimations of mean field calculations, seem to indicate that we are still quite far from the neutron drip line.

- We have obtained similar results in other regions, e.g., for nuclei around ^{208}Pb and for the Ca chain

  L. Coraggio, A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C 80, 021305(R) (2009)

  “ “ “ Phys. Rev C80, 044311 (2009)

- Our calculations in these regions seem to leave little room for sizeable contributions from three-nucleon forces. It is very interesting that the results recently obtained with the chiral $NNLO_{opt}$ *NN* potential lead to the same conclusion. This is somewhat intriguing and certainly deserves further investigation.